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(54) **SYSTEM AND METHOD FOR TEST AND/OR CALIBRATION OF MULTI-CHANNEL RF COMMUNICATION DEVICES**

(71) Applicant: **Keysight Technologies, Inc.**, Santa Rosa, CA (US)

(72) Inventors: **Stephen G. Duffy**, Santa Rosa, CA (US); **Xu Zhao**, Beijing (CN); **Hong-Wei Kong**, Beijing (CN); **Ya Jing**, Beijing (CN)

(73) Assignee: **Keysight Technologies, Inc.**, Santa Rosa, CA (US)

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H04W 76/15	(2018.01)

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(Continued)

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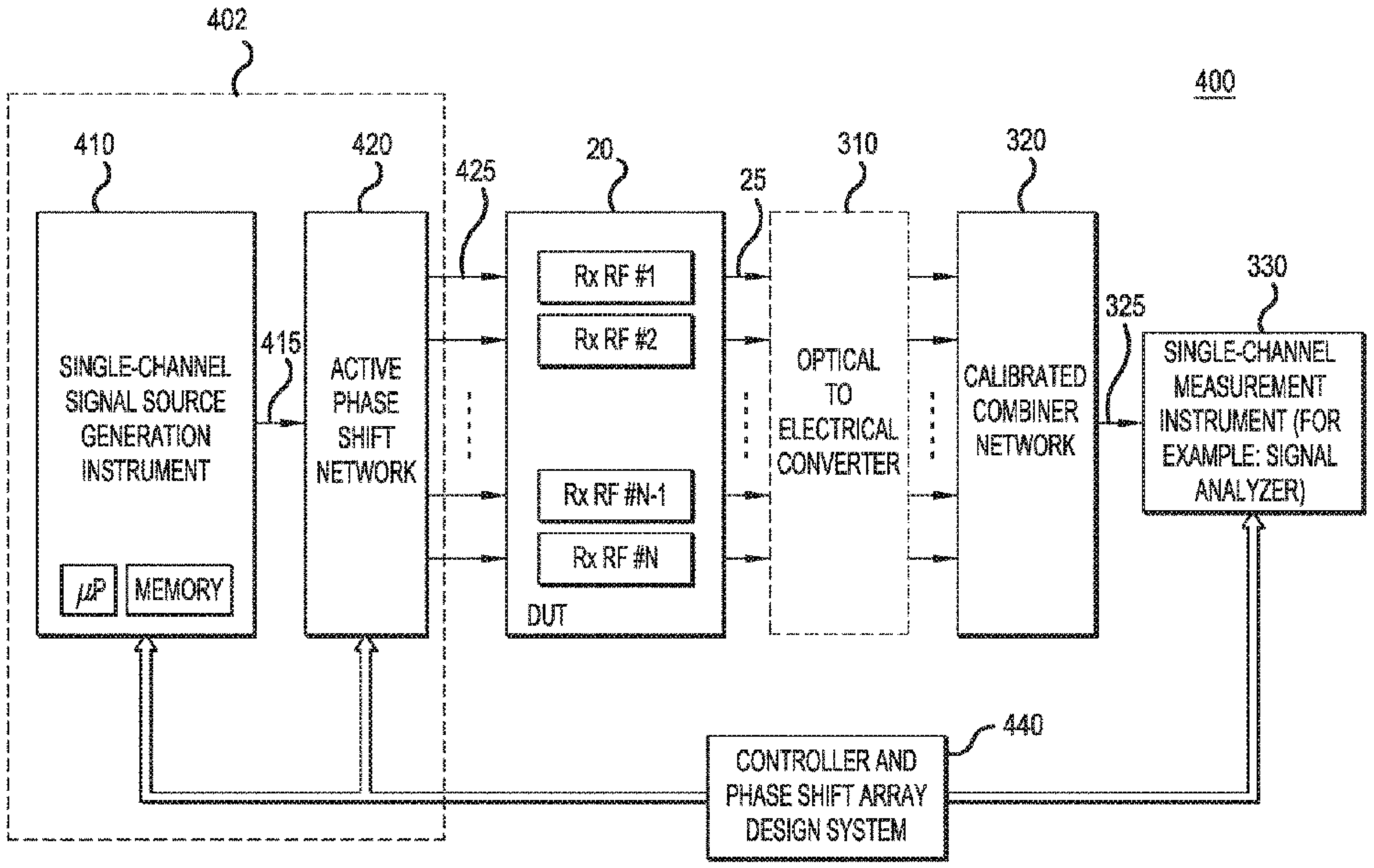
Primary Examiner — Nguyen T Vo

(57) **ABSTRACT**

A test system includes: a signal processor configured to generate a plurality of orthogonal baseband sequences; a signal generator configured to supply the plurality of orthogonal baseband sequences to a corresponding plurality of RF transmitters of a device under test (DUT), wherein the RF transmitters each employ the corresponding orthogonal baseband sequence to generate a corresponding RF signal on a corresponding channel among a plurality of channels of the DUT such that the RF transmitters output a plurality of orthogonal RF signals at a same time; a combiner network configured to combine the plurality of orthogonal RF signals and to output a single signal under test; and a single channel measurement instrument configured to receive the single signal under test and to measure independently therefrom at least one characteristic of each of the RF transmitters. Orthogonal RF test signals may be used similarly to test RF receivers of the DUT.

20 Claims, 5 Drawing Sheets



(51) **Int. Cl.**

H04W 36/14	(2009.01)
H04W 24/06	(2009.01)
H04W 36/24	(2009.01)
H04W 36/28	(2009.01)
H04W 88/02	(2009.01)

(52) **U.S. Cl.**
CPC ***H04W 36/28*** (2013.01); ***H04W 76/15*** (2018.02); *H04W 88/02* (2013.01)

(58) **Field of Classification Search**
CPC ... H04W 88/02; H04B 17/0085; H04B 17/20; H04B 17/121; H04B 17/29; H04B 17/30
See application file for complete search history.

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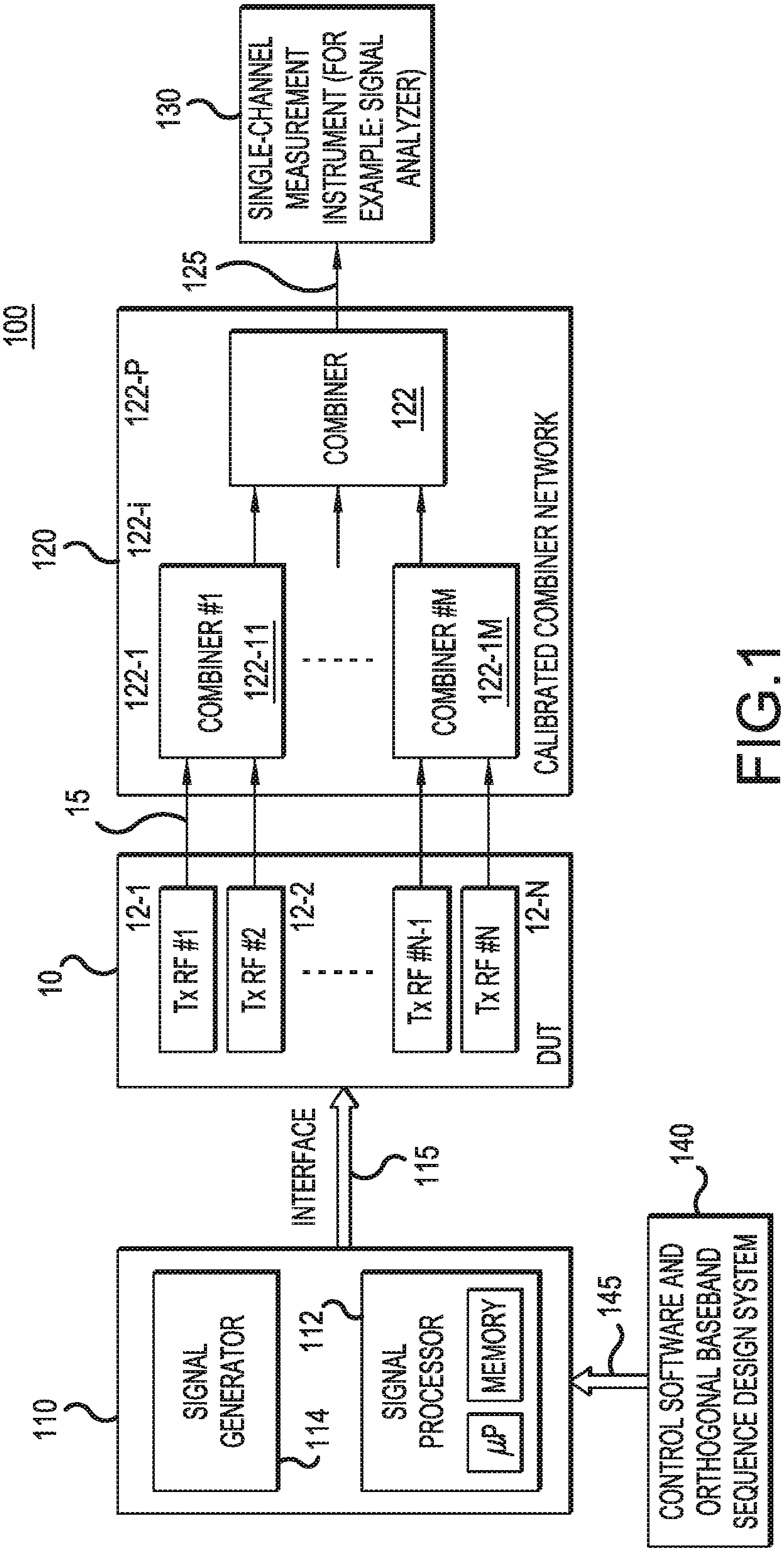
100
130
SINGLE-CHANNEL MEASUREMENT INSTRUMENT (FOR EXAMPLE: SIGNAL ANALYZER)
125
120
122-1
122-i
122-P
COMBINER
122
COMBINER #1
122-11
COMBINER #M
122-1M
CALIBRATED COMBINER NETWORK
15
10
12-1
12-2
12-N
Tx RF #1
Tx RF #2
Tx RF #N-1
Tx RF #N
DUT
INTERFACE
115
110
SIGNAL GENERATOR
114
112
SIGNAL PROCESSOR
μP
MEMORY
145
140
CONTROL SOFTWARE AND ORTHOGONAL BASEBAND SEQUENCE DESIGN SYSTEM

FIG. 1

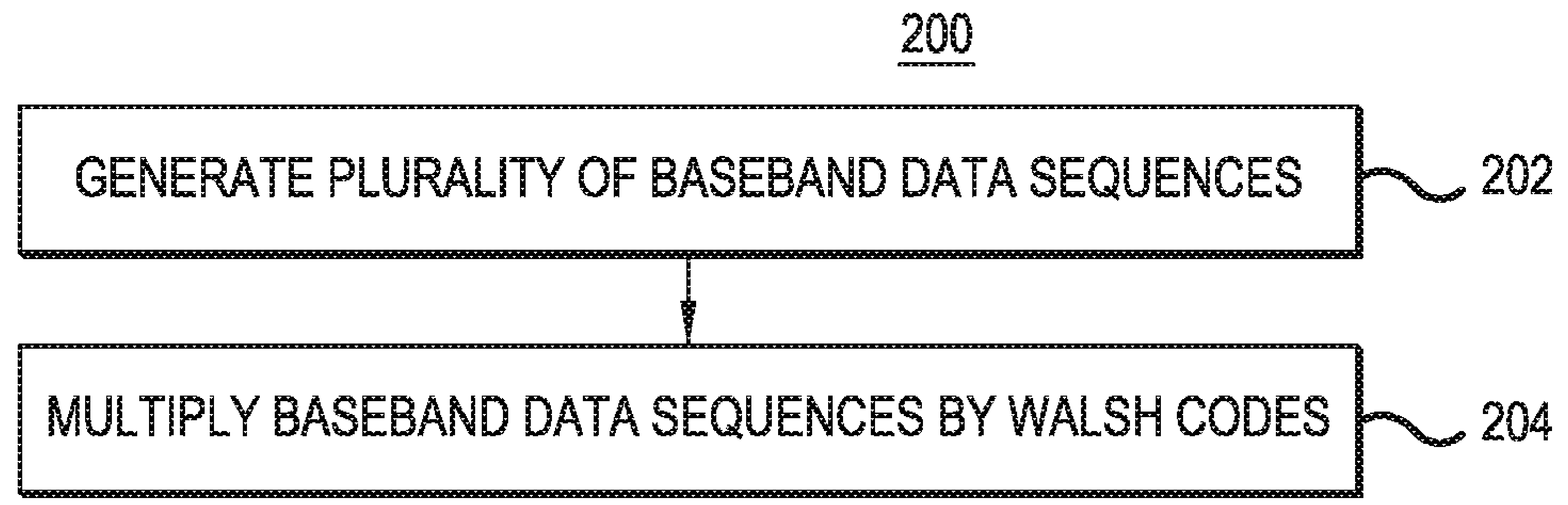

FIG.2A

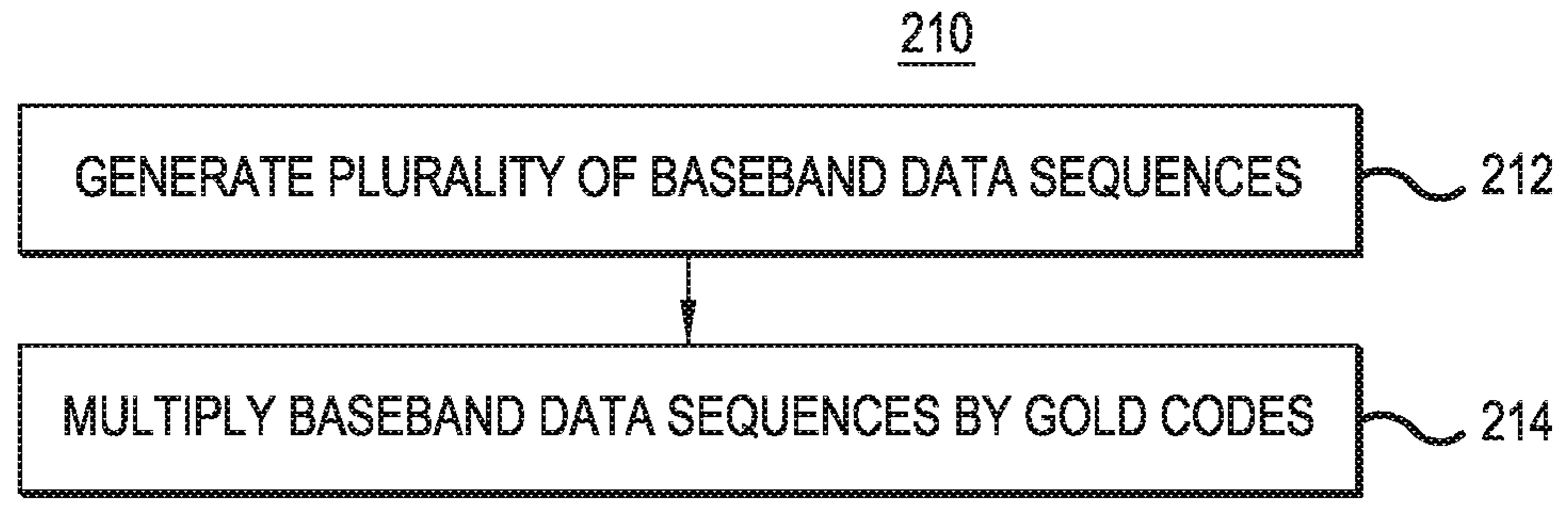

FIG.2B

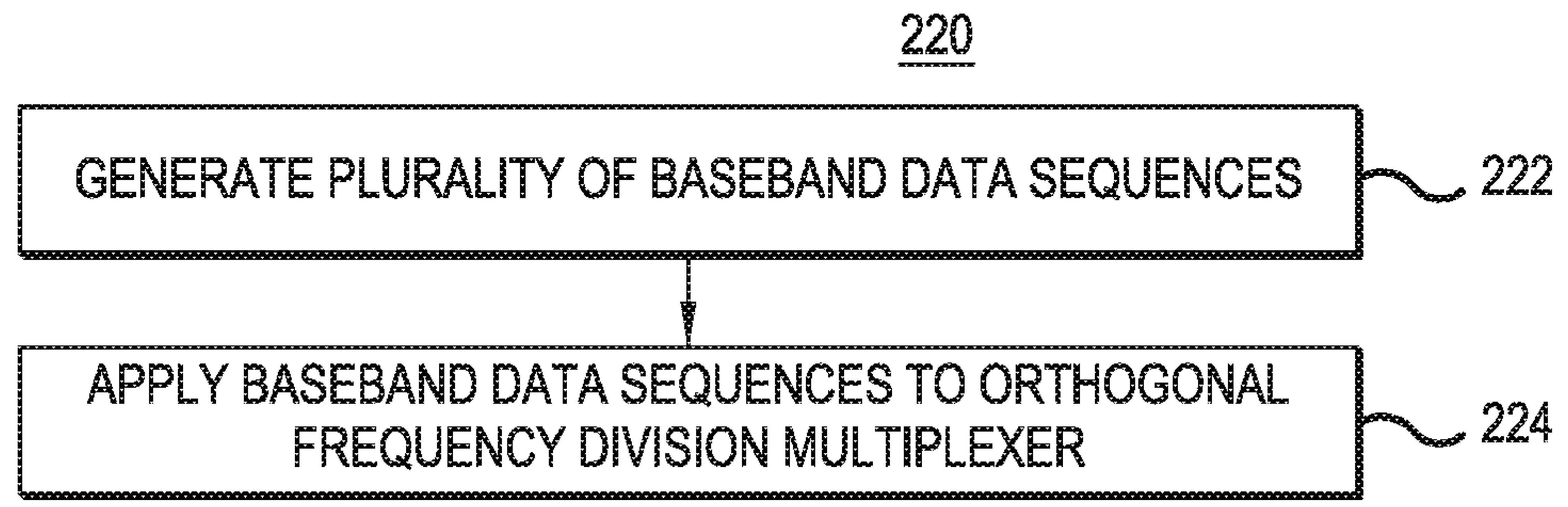

FIG.2C

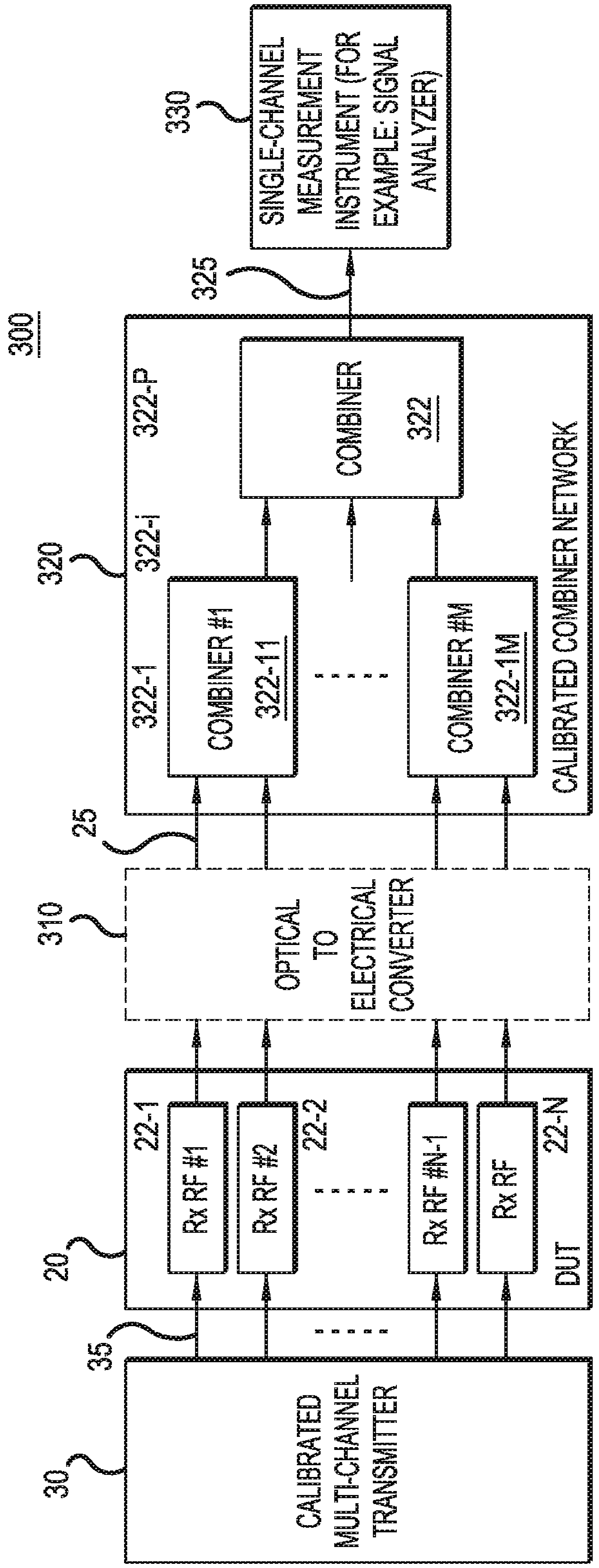
300
30
CALIBRATED MULTI-CHANNEL TRANSMITTER
35
20
Rx RF #1
Rx RF #2
Rx RF #N-1
Rx RF
22-1
22-2
22-N
DUT
310
OPTICAL TO ELECTRICAL CONVERTER
25
320
322-1
322-i
322-P
COMBINER #1
322-11
COMBINER #M
322-1M
COMBINER
322
CALIBRATED COMBINER NETWORK
325
330
SINGLE-CHANNEL MEASUREMENT INSTRUMENT (FOR EXAMPLE: SIGNAL ANALYZER)

FIG.3

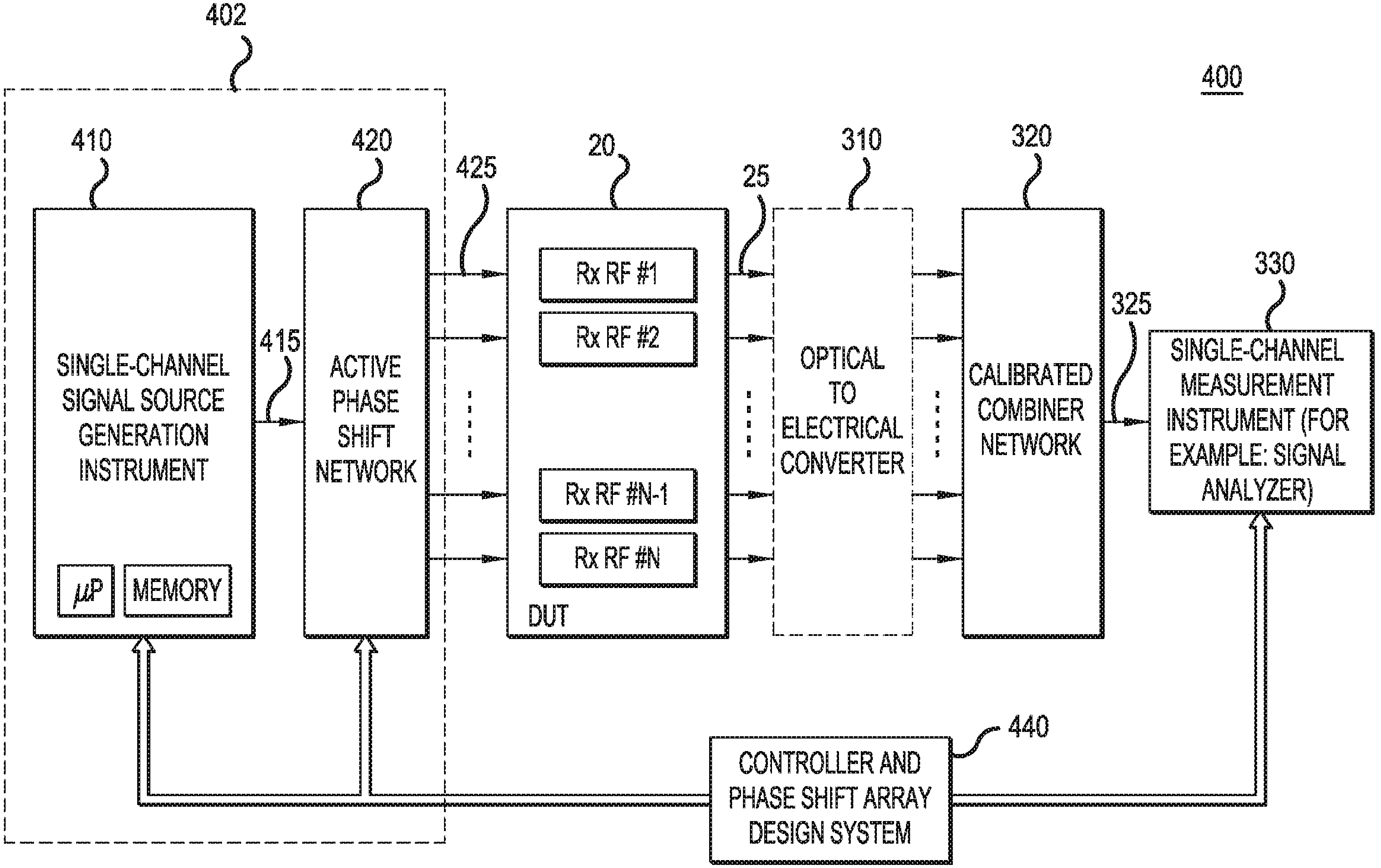
400
402
410
420
425
20
25
310
320
330
325
415
SINGLE-CHANNEL SIGNAL SOURCE GENERATION INSTRUMENT
μP
MEMORY
ACTIVE PHASE SHIFT NETWORK
Rx RF #1
Rx RF #2
Rx RF #N-1
Rx RF #N
DUT
OPTICAL TO ELECTRICAL CONVERTER
CALIBRATED COMBINER NETWORK
SINGLE-CHANNEL MEASUREMENT INSTRUMENT (FOR EXAMPLE: SIGNAL ANALYZER)
440
CONTROLLER AND PHASE SHIFT ARRAY DESIGN SYSTEM

FIG.4

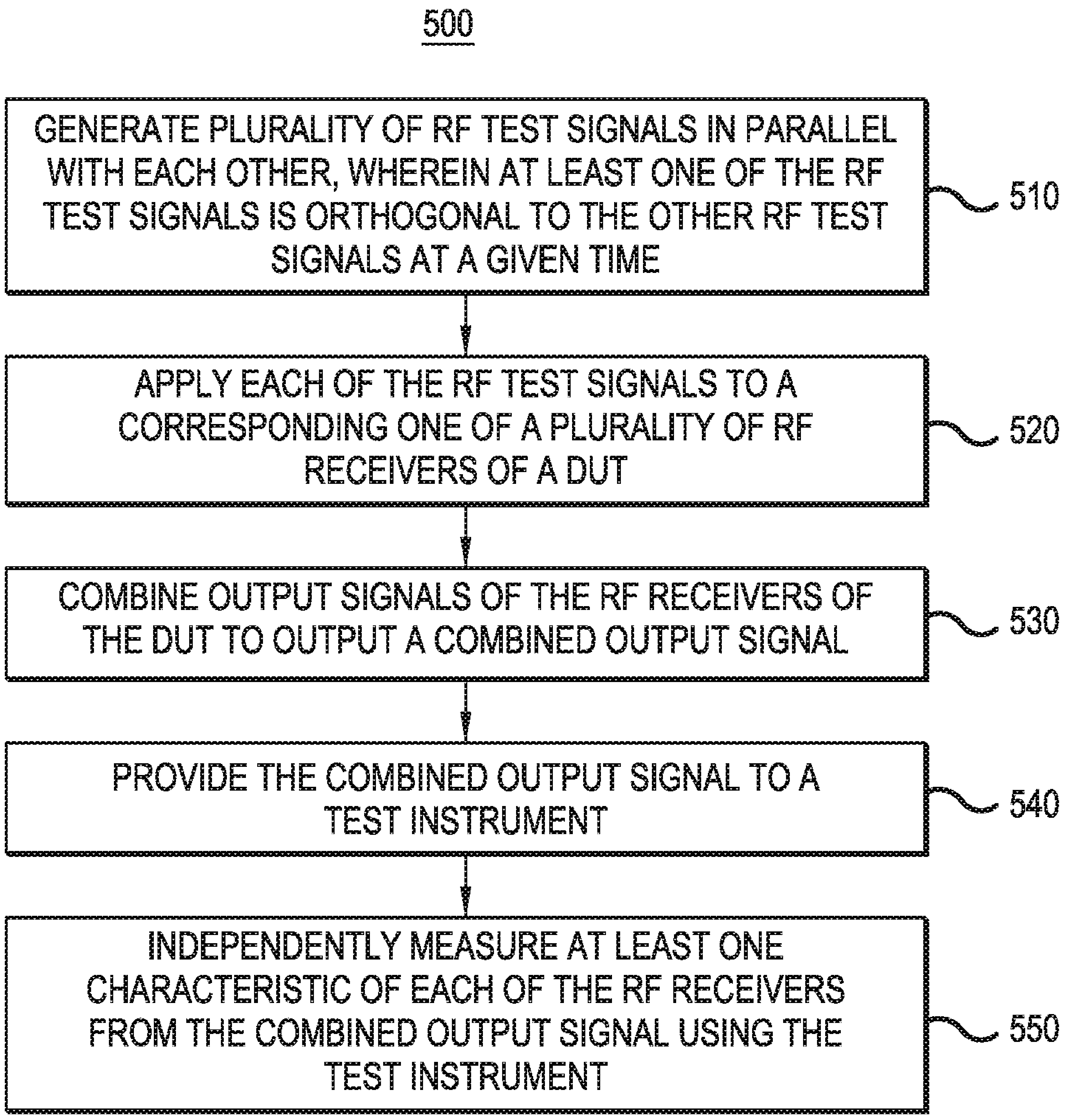
500
GENERATE PLURALITY OF RF TEST SIGNALS IN PARALLEL WITH EACH OTHER, WHEREIN AT LEAST ONE OF THE RF TEST SIGNALS IS ORTHOGONAL TO THE OTHER RF TEST SIGNALS AT A GIVEN TIME
510
APPLY EACH OF THE RF TEST SIGNALS TO A CORRESPONDING ONE OF A PLURALITY OF RF RECEIVERS OF A DUT
520
COMBINE OUTPUT SIGNALS OF THE RF RECEIVERS OF THE DUT TO OUTPUT A COMBINED OUTPUT SIGNAL
530
PROVIDE THE COMBINED OUTPUT SIGNAL TO A TEST INSTRUMENT
540
INDEPENDENTLY MEASURE AT LEAST ONE CHARACTERISTIC OF EACH OF THE RF RECEIVERS FROM THE COMBINED OUTPUT SIGNAL USING THE TEST INSTRUMENT
550

FIG.5

SYSTEM AND METHOD FOR TEST AND/OR CALIBRATION OF MULTI-CHANNEL RF COMMUNICATION DEVICES

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a divisional application of U.S. Pat. No. 10,917,937 under 35 U.S.C. § 120 naming to Steve G. Duffy, et al. inventors. U.S. Pat. No. 10,917,937 is a National Stage Application under 35 U.S.C. § 371 of, and claims priority under 35 U.S.C. § 121 from, International Publication No. WO2016064376A1. The entire disclosures of U.S. Pat. No. 10,917,937 and International Publication U.S. Pat. No. 10,917,937 are specifically incorporated herein by reference.

BACKGROUND

In general RF communication systems and devices, like other electronics, require testing and, in some cases, calibration. Testing and calibration can present challenges in the case of an RF communication system or device which supports multiple transmission (Tx) and reception (Rx) channels.

Some traditional solutions employ a single-channel measurement instrument to test and calibrate each channel of a multi-channel RF communication device individually, one-by-one, in sequence. However, these solutions have some drawbacks. First, the repeated connection and disconnection of the single-channel measurement instrument to the multi-channel RF communication device under test (DUT) using RF connectors will influence the testing accuracy and repeatability. Second, as the number of transmission and/or reception channels increases, the time required to perform test and calibration also increases. In particular, in the case of massive multi-input, multi-output (MIMO) communication systems which are now being developed and deployed, the number of channels is very large (in many cases more than 64) and as a result testing each of these channels one-by-one is very time consuming and in fact as the number of channels increases, the time required can be prohibitive.

Some other solutions use multiple test instruments, or a multi-channel test instrument, to test channels in parallel. However, a disadvantage of this approach is that when the number of channels is very large, the test instruments, or multi-channel test instrument, becomes too expensive and even impractical when the number of channels is much greater than 8.

Thus it would be desirable to provide a more convenient and more reliable method and system to test and calibrate the performance of a multi-channel RF communication system or device.

SUMMARY

In accordance with a representative embodiment, a test system, comprises: a test signal generator, comprising: a single channel signal source configured to output a single channel signal, and a phase shift network configured to receive the single channel signal and in response thereto to output a plurality of RF test signals in parallel with each other. The phase shift network is further configured to shift a phase of one or more of the RF test signals so as to make at least a selected one of the RF test signals orthogonal to the other RF test signals. The test system further comprises a combiner network having a plurality of inputs each configured to receive one of a plurality of receive signals, each receive signal being produced from a corresponding one of a plurality of RF receivers of a device under test (DUT) in response to the RF test signals. The combiner is configured to combine the plurality of receive signals and to output a combined output signal. The test system further comprises a single channel measurement instrument configured to receive the combined output signal and to measure therefrom at least one characteristic of each of the RF receivers.

In accordance with another representative embodiment, a test system, comprises: a test signal generator, comprising: a single channel signal source, comprising a processor and a memory, which stores instructions, which when executed by the processor cause the processor to: generate a plurality of RF test signals in parallel with each other, wherein at least one of the RF test signals is orthogonal to the other RF test signals at a given time; apply each of the plurality of RF test signals to a corresponding one of the plurality of RF receivers of the DUT; combine a plurality of receive signals each produced from one of the plurality of RF receivers of the DUT in response to the corresponding one of the plurality of RF test signals, to output a combined output signal; provide the combined output signal to a test instrument; and employ the test instrument to independently measure at least one characteristic of each of the RF receivers from the combined output signal.

In yet another example embodiment, a method is provided for testing a device under test (DUT) including a plurality of RF receivers. The method comprises: generating a plurality of RF test signals in parallel with each other, wherein at least one of the RF test signals is orthogonal to the other RF test signals at a given time; applying each of the plurality of RF test signals to a corresponding one of the plurality of RF receivers of the DUT; combining a plurality of received signals each produced from one of the plurality of RF receivers of the DUT in response to the corresponding one of the plurality of RF test signals, to output a combined output signal; and providing the combined output signal to a test instrument; and employing the test instrument to independently measure at least one characteristic of each of the RF receivers from the combined output signal.

BRIEF DESCRIPTION OF THE DRAWINGS

The example embodiments are best understood from the following detailed description when read with the accompanying drawing figures. In fact, the dimensions may be arbitrarily increased or decreased for clarity of discussion. Wherever applicable and practical, like reference numerals refer to like elements.

FIG. **1** illustrates a first example embodiment of a system for testing a multi-channel RF system or device under test (DUT).

FIGS. **2**A, **2**B and **2**C illustrate three embodiments of methods of generating orthogonal test signals for testing a multi-channel RF system or device under test (DUT).

FIG. **3** illustrates a second example embodiment of a system for testing a multi-channel RF system or device under test (DUT).

FIG. **4** illustrates a third example embodiment of a system for testing a multi-channel RF system or device under test (DUT).

FIG. **5** is a flowchart of an example embodiment of a method of testing a multi-channel RF system or device under test (DUT).

DETAILED DESCRIPTION

In the following detailed description, for purposes of explanation and not limitation, example embodiments disclosing specific details are set forth in order to provide a thorough understanding of an embodiment according to the present teachings. However, it will be apparent to one having ordinary skill in the art having had the benefit of the present disclosure that other embodiments according to the present teachings that depart from the specific details disclosed herein remain within the scope of the appended claims. Moreover, descriptions of well-known apparati and methods may be omitted so as to not obscure the description of the example embodiments. Such methods and apparati are clearly within the scope of the present teachings.

Unless otherwise noted, when a first device is said to be connected to a second device, this encompasses cases where one or more intermediate devices may be employed to connect the two devices to each other. However, when a first device is said to be directly connected to a second device, this encompasses only cases where the two devices are connected to each other without any intermediate or intervening devices. Similarly, when a signal is said to be coupled to a device, this encompasses cases where one or more intermediate devices may be employed to couple the signal to the device. However, when a signal is said to be directly coupled to a device, this encompasses only cases where the signal is directly coupled to the device without any intermediate or intervening devices.

FIG. **1** illustrates a first example embodiment of a test system **100** for testing a multi-channel RF system or device under test (DUT) **10**. Test system **100** includes a signal source **110**, a combiner network **120**, and a single channel measurement instrument **130**. Test system **100** may also further include a signal design system **140**. In particular, test system **100** is an embodiment of a system for testing and/or calibrating a plurality of RF transmitters of a multi-channel RF device or system, specifically a multi-channel RF communication device or system.

In the example embodiment, DUT **10** is connected to signal source **110** via an interface **115**. Here, it is assumed that DUT **10** includes a plurality (N) of RF transmitters **12**, e.g., **12-1**, **12-2**, . . . , **12**-N which are capable of operating independently from each other. Each RF transmitter **12** receives corresponding data, for example in the form of a baseband sequence, and is capable of generating therefrom a RF transmit signal **15**, wherein one or more parameters of RF transmit signal **15** (e.g., a phase or frequency shift or modulation) is changed depending on the data so that the data is represented in RF transmit signal **15**. In the example embodiment, interface **115** may comprise a baseband interface for receiving a plurality of baseband sequences, and/or may comprise an optical interface wherein the baseband sequences are provided on one or more optical signal carriers. In some embodiments, DUT **10** may be a massive multi-input, multi-output (MIMO) communication system having many RF transmitters **12**. In some embodiments where DUT **10** is a MIMO system, DUT **10** may have at least N=64 RF transmitters **12-1** . . . **12**-N. In some embodiments, DUT **10** may have N=400 or more RF transmitters **12-1** . . . **12**-N.

In the illustrated embodiment, signal source **110** includes a signal processor **112** and a signal generator **114**. Signal processor **112** may further include a digital microprocessor and memory, which may include volatile and/or nonvolatile memory, including random access memory (RAM), read only memory—for example electrically erasable programmable read only memory (EEPROM), FLASH memory, etc. In some embodiments, the memory may store instructions to be executed by the digital microprocessor to cause the digital microprocessor to perform one or more algorithms for generating a plurality of baseband test sequences to be supplied to DUT **10**, as discussed in greater detail below. Signal processor **112** may also include firmware, one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), programmable gate arrays, etc.

In the illustrated embodiment, combiner network **120** is configured with a plurality of combiner stages **122-1**, . . . , **122**-*i*, . . . , **122**-P, wherein each combiner stage **122**-*i* may include one or more combiners **122**. In the illustrated embodiment, each combiner **122** is a two-input device. Other configurations of a combiner network are possible. For example, in other embodiments, a combiner network may include a plurality of stages of four-input devices, or even a single stage with one N-input device. Combiner network **120** is configured to output a single signal under test **125** produced by combining RF transmit signals **15** output by RF transmitters **12-1** . . . **12**-N.

In a beneficial feature, combiner network **120** may be calibrated so that the transfer function (e.g., signal amplitude loss and or phase shift) from each RF transmit signal **15** to the output signal under test **125** through combiner network **120** is known absolutely and/or with respect to each other (i.e., the losses and phase shifts for the different RF transmit signals **15** are known with respect to each other). Calibration data for the various RF transmit signals **15** may be stored in memory, for example a memory of single channel measurement instrument **130**, such that single channel measurement instrument **130** may produce calibrated measurement or test results for each of the RF transmitters **12-1** . . . **12**-N of DUT **10**.

Single channel measurement instrument **130** is connected to an output of combiner network **120** to receive signal under test **125** therefrom. In some embodiments, single channel measurement instrument **130** may comprise an RF test instrument. In some embodiments, single channel measurement instrument **130** may comprise a single channel signal analyzer, e.g., an RF signal analyzer, such as a spectrum analyzer. However, in general, single channel measurement instrument **130** may be any test or measurement instrument which can measure one or more parameters of any RF transmit signal **15** generated an RF transmitter **12** by DUT **10**. In some embodiments, test system **100** may include more than one single channel measurement instrument which may operate in parallel to measure different parameters of single signal under test **125** output by combiner network **120**.

In general, as noted above, DUT **10** includes a plurality of RF transmitters **12-1** . . . **12**-N which all may operate independently from each other. Accordingly, in general non-orthogonal operation, RF transmit signals **15** transmitted by RF transmitters **12-1** . . . **12**-N may occupy the same spectral space at the same time as each other and could interfere which each other. In that case, it could be difficult or impossible to separately or individually test or measure any parameter of any one of the RF transmitters **12-1** . . . **12**-N from the combined single signal under test **125** output by combiner network **120**.

To address this issue, as discussed in greater detail below, in test system **100**, signal generator **114** is configured to supply a corresponding plurality of orthogonal or substantially orthogonal baseband sequences to RF transmitters **12-1** . . . **12**-N of DUT **10**. As a result, the RF transmit signals **15** generated by RF transmitters **12-1** . . . **12**-N of DUT **10** are also orthogonal or substantially orthogonal to each other. Thus, even though the RF transmit signals **15** are combined by combiner network **120** to produce a single signal under test **125** output by combiner network **120**, single channel measurement instrument **130** may resolve or separate each individual RF transmit signal **15** from the signal under test **125** so as to individually test or measure one or more parameters of any one of the RF transmitters **12-1** . . . **12**-N from the combined single signal under test **125** output by combiner network **120**. An example operation of test system **100** will now be described to better illustrate these principles.

In operation, signal processor **112** generates a plurality of orthogonal baseband sequences. Although it is understood that as a practical matter the plurality of orthogonal baseband sequences in some embodiments may not be perfectly orthogonal to each other and may have some small residual non-orthogonal components, in the description to follows orthogonal or substantially orthogonal baseband sequences will be referred to generally as "orthogonal baseband sequences."

FIGS. **2**A, **2**B and **2**C illustrate three embodiments of methods **200**, **210** and **220**, respectively, of generating orthogonal baseband sequences for testing a multi-channel RF system or device under test (DUT).

Method **200** includes an operation **202** of generating a plurality of baseband data sequences. In some embodiments, each of the plurality of baseband data sequences may comprises a pseudorandom bitstream. Method **200** also includes an operation **204** of multiplying the baseband data sequences by a Walsh code or Walsh matrix to produce a plurality of orthogonal baseband sequences.

Method **210** includes an operation **212** of generating a plurality of baseband data sequences. In some embodiments, each of the plurality of baseband data sequences may comprises a pseudorandom bitstream. Method **210** also includes operation **214** of multiplying each of the baseband data sequences by a corresponding Gold code to produce a plurality of orthogonal baseband sequences.

Method **220** includes an operation **222** of generating a plurality of baseband data sequences. In some embodiments, each of the plurality of baseband data sequences may comprises a pseudorandom bitstream. Method **200** also includes operation **224** of applying the baseband data sequences to an orthogonal frequency divisional multiplexer to generate an orthogonal frequency division multiplexed (OFDM) signal comprising a plurality of orthogonal baseband sequences.

Although methods **200**, **210**, and **220** have been illustrated as examples, other methods of generating a plurality of orthogonal baseband sequences are contemplated.

In some embodiments, one or more of the operations of methods **200**, **210** or **220** may be performed by a digital microprocessor and memory of signal processor **112**, as discussed above. For example, in some embodiments the digital microprocessor may execute an algorithm according to instructions stored in memory (e.g., nonvolatile memory) to generate the plurality of baseband data sequences, for example pseudorandom bitstreams. In some embodiments, the digital microprocessor may execute an algorithm according to instructions stored in memory (e.g., nonvolatile memory) to generate Walsh codes or a Walsh matrix for the baseband data sequences. In some embodiments, the digital microprocessor may execute an algorithm to multiply the Walsh codes or Walsh matrix with the baseband data sequences to generate the plurality of orthogonal baseband sequences.

In some embodiments, the baseband data sequences or the orthogonal baseband sequences may be stored in memory, for example a nonvolatile memory such as an EEPROM or FLASH device, and may be read from the nonvolatile memory by the digital microprocessor.

In some embodiments, the baseband data sequences, Walsh codes, and/or the resultant orthogonal baseband sequences may be designed by signal design system **140** and communicated therefrom to signal source **110**, and in particular signal processor **112**. In some embodiments, signal design system **140** may comprise a general purpose computer including one or more digital microprocessors, memory (including volatile and/or nonvolatile memory), data storage (e.g., a hard disk or FLASH memory drive), one or more interfaces **145** (e.g., an Ethernet port, wireless network interface, etc.) for communicating with signal source **110**, and a user interface which may include one or more of a display, keyboard, keypad, touchscreen, mouse, trackball, microphone, etc. In some embodiments, a user may execute one or more software algorithms stored in memory and/or data storage of signal design system **140** to design or set parameters for the baseband data sequences, Walsh codes, and/or the resultant orthogonal baseband sequences employed by signal processor **112**, and may communicate this data to signal processor **112** via interface **145**. In some embodiments, signal design system **140** may only be connected to signal source **110** during a system design or system configuration phase for test system **100**.

In some embodiments, signal design system **140** and all of the data and parameters necessary for operation of signal source **110** and signal processor **112** may be stored in nonvolatile memory in signal source **110** or signal processor **112**.

Signal generator **114** is configured to supply the plurality of orthogonal baseband sequences to the corresponding plurality of RF transmitters **12** of DUT **10** via interface **115**. In some embodiments, signal generator **114** may be configured to continuously supply the plurality of orthogonal baseband sequences to the corresponding plurality of RF transmitters **12-1** . . . **12**-N of DUT **10** via interface **115** during testing of DUT **10**. In other embodiments, the orthogonal baseband sequences may comprise relatively long data patterns of fixed length which are transmitted over and over repeatedly by RF transmitters **12-1** . . . **12**-N. In that case, in some embodiments, signal generator **114** may be configured to supply the plurality of orthogonal baseband sequences to DUT **10** one time via interface **115**, and DUT **10** may store the orthogonal baseband sequences in internal memory of DUT **10** and apply each orthogonal baseband sequence to a corresponding RF transmitter **12** during testing.

In some embodiments, signal generator **114** may be configured to supply the plurality of orthogonal baseband sequences to DUT **10** via interface **115** sequentially, one at a time. In some embodiments, signal generator **114** may be configured to supply the plurality of orthogonal baseband sequences to the corresponding plurality of RF transmitters **12-1** . . . **12**-N of DUT **10** via interface **115** in parallel with each other.

In some embodiments, interface **115** may include an electrical interface. In that case, in some embodiments, signal generator **114** may be configured to supply the plurality of orthogonal baseband sequences to DUT **10** via the electrical interface as baseband data patterns. In some embodiments, interface **115** may include an optical interface. In that case, signal generator **114** may be configured to modulate the orthogonal baseband sequences onto one or more optical carriers supplied to DUT via the optical interface.

RF transmitters **12-1** . . . **12**-N each employ the corresponding orthogonal baseband sequence to generate a corresponding RF transmit signal **15** on a corresponding channel among a plurality of channels of DUT **10**, such that RF transmitters **12-1** . . . **12**-N output a plurality of orthogonal RF transmit signals **15** at the same time as each other.

Combiner network **120** combines the plurality of orthogonal RF transmit signals **15** produced by RF transmitters **12-1** . . . **12**-N to produce and output a single signal under test **125**. Combiner network maintains or substantially maintains the orthogonality between the RF transmit signals **15** produced by RF transmitters **12-1** . . . **12**-N when combining the RF transmit signals **15** to produce signal under test **125**.

Single channel measurement instrument **130** receives single signal under test **125** and therefrom measures independently at least one characteristic of each of RF transmitters **12-1** . . . **12**-N of DUT **10**. As noted above since the RF transmit signals **15** produced by RF transmitters **12-1** . . . **12**-N which are included in signal under test **125** are all orthogonal or substantially orthogonal to each other, mutual interference is minimal and single channel measurement instrument **130** is able to separate or resolve each individual RF transmit signal **15** to measure at least one characteristic of the corresponding RF transmitter **12**. In some embodiments, single channel measurement instrument **130** sequentially measures one or more characteristics of RF transmitters **12-1** . . . **12**-N, one at a time. In various embodiments, single channel measurement instrument **130** may measure one or more of the following characteristics of each RF transmitter **12**: output power level, occupied bandwidth, signal-to-noise ratio (SNR), harmonic output levels, harmonic distortion, signal-to-noise-plus-interference ratio (SNIR), etc.

FIG. **3** illustrates a second example embodiment of a test system **300** for testing a multi-channel RF device under test (DUT) **20**. Test system **300** includes a combiner network **320** and a single channel measurement instrument **330**. Test system **300** may also further include, optionally, an optical-to-electrical converter **310**. In particular, test system **300** is an embodiment of a system for testing and/or calibrating a plurality RF receivers of a multi-channel RF device or system, specifically a multi-channel RF communication device or system.

Test system **300** assumes the availability of a calibrated multi-channel transmitter **30** which may be configured to generate and output a plurality of RF test signals **35** in parallel with each other, wherein at least one of the RF test signals **35** is orthogonal to the other RF test signals at a given time. In some embodiments, calibrated multi-channel transmitter **30** may be configured to generate a plurality of RF test signals **35** in parallel with each other, wherein each of the RF test signals **35** is orthogonal to all of the other RF test signals at a given time. In some embodiments, calibrated multi-channel transmitter **30** may be a transmission portion of DUT **20** which includes many RF transmitters, for example as illustrated in FIG. **1**.

Here, it is further assumed that DUT **20** includes a plurality (N) of RF receivers **22**, e.g., **22-1**, **22-2**, . . . , **22**-N which are capable of operating independently from each other. Each RF receiver **22** receives a corresponding RF test signal **35** from calibrated multi-channel transmitter **30**, wherein one or more parameters of RF test signal **35** (e.g., an amplitude, phase, or frequency shift or modulation) is changed depending on data which it transmits, so that the data is represented in the transmit RF signal. In some embodiments, DUT **20** may be a massive multi-input, multi-output (MIMO) communication system having many RF receivers **22-1** . . . **22**-N. In some embodiments where DUT **20** is a MIMO system, DUT **20** may have at least N=64 RF receivers **22-1** . . . **22**-N. In some embodiments, DUT **10** may have N=400 or more RF receivers **22-1** . . . **22**-N.

In the example embodiment, each of the RF receivers **22-1** . . . **22**-N of DUT **20** outputs an optical output signal comprising a baseband sequence provided on one or more optical signal carriers. In particular, the baseband sequences output by RF receivers **22-1** . . . **22**-N of DUT **20** are orthogonal or substantially orthogonal to each other. The optical output signals output by RF receivers **22-1** . . . **22**-N of DUT **20** are provided to combiner network **320** via optional optical-to-electrical converter **310**. Optical-to-electrical converter **310** converts the optical output signals from RF receivers **22-1** . . . **22**-N of DUT **20** into RF or intermediate frequency (IF) receive signals **25** which carry the orthogonal baseband sequences and which are then provided from optical-to-electrical converter **310** to combiner network **320**.

In other embodiments, RF receivers **22-1** . . . **22**-N of DUT **20** may include RF or intermediate frequency (IF) outputs. In that case, the orthogonal baseband sequences may be output from RF receivers **22-1** . . . **22**-N on RF or IF carriers, in which case optical-to-electrical converter **310** may be omitted and the RF or IF receive signals **25** may be provided directly from RF receivers **22-1** . . . **22**-N of DUT **20** to combiner network **320**.

In the illustrated embodiment, combiner network **320** is configured with a plurality of combiner stages **322-1**, . . . , **322**-*i*, . . . , **322**-P, wherein each combiner stage **322**-*i* may include one or more combiners **322**. In the illustrated embodiment, each combiner **322** is a two-input device. Other configurations of a combiner network are possible. For example, in other embodiments, a combiner network may include a plurality of stages of four-input devices, or even a single stage with one N-input device. Combiner network **320** is configured to output a single combined output signal **325** produced by combining receive signals **25** output by RF receivers **22-1** . . . **22**-N.

In a beneficial feature, combiner network **320** may be calibrated so that the transfer function (e.g., signal amplitude loss and or phase shift) from each RF receive signal **25** to the single combined output signal **325** through combiner network **320** is known absolutely and/or with respect to each other (i.e., the losses and phase shifts for the different RF receive signals **25** are known with respect to each other). Calibration data for the various RF receive signals **25** may be stored in memory, for example a memory of single channel measurement instrument **130**, such that single channel measurement instrument **130** may produce calibrated measurement or test results for each of the RF receivers **22-1** . . . **22**-N of DUT **20**.

Single channel measurement instrument **130** is connected to an output of combiner network **320** to receive single combined output signal **325** therefrom. In some embodiments, single channel measurement instrument **130** may comprise an RF test instrument. In some embodiments, single channel measurement instrument **130** may comprise a single channel signal analyzer, e.g., an RF signal analyzer, such as a spectrum analyzer. However, in general, single channel measurement instrument **130** may be any test or measurement instrument which can select (based on the orthogonal properties of the signal) and measure one or more parameters of any RF receive signal **25** generated an RF receiver **22** by DUT **20**. In some embodiments, test system **300** may include more than one single channel measurement instrument which may operate in parallel to measure different parameters of single combined output signal **325** output by combiner network **320**.

In general, as noted above, DUT **20** includes a plurality of RF receivers **22-1** . . . **22**-N which all may operate independently from each other.

Accordingly, in general (non orthogonal) operation, RF signals received by RF receivers **22-1** . . . **22**-N may occupy the same spectral space at the same time as each other and could interfere which each other. In that case, it could be difficult or impossible to separately or individually test or measure any parameter of any one of the RF receivers **22-1** . . . **22**-N from the single combined output signal **325** output by combiner network **320**.

To address this issue, as discussed in greater detail below, in test system **300**, calibrated multi-channel transmitter **30** is configured to supply a corresponding plurality of orthogonal or substantially orthogonal RF test signals **35** to RF receivers **22-1** . . . **22**-N of DUT **20**. As a result, the receive signals **25** generated by RF receivers **22-1** . . . **22**-N of DUT **20** are also orthogonal or substantially orthogonal to each other. Thus, even though the receive signals **25** are combined by combiner network **320** to produce and output a single combined output signal **325**, single channel measurement instrument **130** may resolve or separate each individual receive signal **25** from the single combined output signal **325** so as to individually test or measure one or more parameters of any one of the RF receivers **22-1** . . . **22**-N from the single combined output signal **325** output by combiner network **320**. An example operation of test system **300** will now be described to better illustrate these principles.

Calibrated multi-channel transmitter **30** is configured to supply a corresponding plurality of orthogonal or substantially orthogonal RF test signals **35** to RF receivers **22-1** . . . **22**-N of DUT **20**.

RF receivers **22-1** . . . **22**-N each process the corresponding orthogonal RF test signal to generate a corresponding receive RF test signal **35** on a corresponding channel among a plurality of channels of DUT **20**, such that RF receivers **22-1** . . . **22**-N output a plurality of orthogonal RF receive signals **25** at the same time as each other.

Combiner network **320** combines the plurality of receive signals **25** produced by RF receivers **22-1** . . . **22**-N to produce the single combined output signal **325**. Combiner network maintains or substantially maintains the orthogonality between the RF receive signals **25** produced by RF receivers **22-1** . . . **22**-N when combining the RF receive signals **25** to produce single combined output signal **325**.

Single channel measurement instrument **130** receives single combined output signal **325** and therefrom measures independently at least one characteristic of each of the RF receivers **22-1** . . . **22**-N of DUT **20**. As noted above since the RF test signals **35** produced by calibrated multi-channel transmitter **30** are all orthogonal to each other, receive signals **25** are also orthogonal to each other. Accordingly, mutual interference is minimal and single channel measurement instrument **130** is able to separate or resolve each individual receive signal **25** to measure at least one characteristic of the corresponding RF receiver **22**. In some embodiments, single channel measurement instrument **130** sequentially measures one or more characteristics of RF receivers **22-1** . . . **22**-N, one at a time.

FIG. **4** illustrates a third example embodiment of a test system **400** for testing a multi-channel RF device under test (DUT). As will be explained in greater detail below, a principal difference between test system **300** and test system **400** is the method of creating orthogonality between the RF test signals. Test system **300** uses baseband channel coding to achieve the orthogonality, while test system **400** employs phase shifting. Test system **400** includes a test signal generator **402**, combiner network **320**, single channel measurement instrument **330** and controller and phase shift array design system **440**. Test system **400** may also further include, optionally, optical-to-electrical converter **310**. In particular, test system **400** is an embodiment of a system for testing and/or calibrating a plurality of RF receivers of a multi-channel RF device or system, specifically a multi-channel RF communication device or system.

Whereas test system **300** described above assumed the availability of a calibrated multi-channel transmitter which could be configured to generate a plurality of RF test signals in parallel with each other, wherein at least one of the RF test signals is orthogonal to the other RF test signals at a given time, in contrast, test system **400** provides a test signal generator **402** which includes a single-channel signal source **410** and a phase shift network (e.g., an active phase shift network) **420** which cooperate to output a plurality of RF test signals **435** in parallel with each other, wherein at least one of the RF test signals **435** is orthogonal to the other RF test signals at a given time. Test signal generator **402** includes one or more interfaces to controller and phase shift array design system **440** for controlling operations thereof, as described below.

Single-channel signal source **410** is configured to generate and output a single channel signal **415**, in particular an RF signal which carries baseband data, whose characteristics match those required for reception by RF receivers **22**. Single-channel signal source **410** may generate single channel signal **415** in response to a signal design produced by controller and phase shift array design system **440**.

In some embodiments, single-channel signal source **410** may include a digital microprocessor and memory, which may include volatile and/or nonvolatile memory, including random access memory (RAM), read only memory—for example electrically erasable programmable read only memory (EEPROM), FLASH memory, etc. In some embodiments, the memory may store instructions to be executed by the digital microprocessor to cause the digital microprocessor to perform one or more algorithms for generating single channel signal **415**. Single-channel signal source **410** may also include firmware, one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), programmable gate arrays, etc.

In some embodiments, single channel signal **415** may be designed by controller and phase shift array design system **440** and communicated therefrom to single-channel signal source **410**. In some embodiments, controller and phase shift array design system **440** may comprise a general purpose computer including one or more digital microprocessors, memory (including volatile and/or nonvolatile memory), data storage (e.g., a hard disk or FLASH memory drive), one or more interfaces (e.g., an Ethernet port, wireless network interface, etc.) for communicating with test signal generator **402**, and a user interface which may include one or more of a display, keyboard, keypad, touchscreen, mouse, trackball, microphone, etc. In some embodiments, a user may execute one or more software algorithms stored in memory and/or data storage of signal design system **140** to design or set parameters for single channel signal and may communicate this data to single-channel signal source **410**. In some embodiments, the parameters necessary for generating single channel signal **415** may be stored in nonvolatile memory in single-channel signal source **410**.

Single-channel signal source **410** is configured to supply single channel signal **415** to phase shift network **420** which may be an active phase shift network.

Phase shift network **420** is configured to receive single channel signal **415** and in response thereto to output a plurality of RF test signals **425** in parallel with each other, wherein phase shift network **420** is further configured to shift the phase of one or more of the RF test signals **425** so as to make at least a selected one of the RF test signals **425** orthogonal to the other RF test signals **425**. In some embodiments, phase shift network **420** is configured to shift the phase of one or more of the RF test signals **425** so as to make all of the RF test signals **425** orthogonal to each other. Phase shift network **420** may be an active device that can shift the phase for all the RF test signals **425** independently according under the design and/or control of controller and phase shift array design system **440** to create some form of orthogonally among RF test signals **425**.

DUT **20**, combiner network **320**, and single channel measurement instrument **330** are the same as the corresponding elements in test system **300** of FIG. **4**, so a repeated description thereof will not be provided.

FIG. **5** is a flowchart of an example embodiment of a method **500** of testing a multi-channel RF system or device. In some embodiments, method **500** may be employed to test and/or calibrate a plurality of RF receivers of a multi-channel RF device or system, specifically a multi-channel RF communication device or system, for example a massive multi-input, multi-output (MIMO) communication system. In some embodiments, method **500** may be performed by test system **300** or test system **400** to measure one or more characteristics of the receivers of DUT **20**.

Method **500** includes an operation **510** of generating a plurality of RF test signals in parallel with each other, wherein at least one of the RF test signals is orthogonal to the other RF test signals at a given time.

Method **500** also includes an operation **520** of applying each of the RF test signals to a corresponding one of a plurality of RF receivers of a DUT such as RF receivers **22** of DUT **20** as shown in FIGS. **3** and **4** and described above.

Method **500** also includes an operation **530** of combining receive signals of the RF receivers of the DUT to output a combined output signal. In some embodiments, the receive signals may be combined via a combiner network, such as combiner network **320** as shown in FIGS. **3** and **4** and described above.

Method **500** also includes an operation **540** of providing the combined output signal to a test instrument (e.g., a measurement instrument).

Method **500** also includes an operation **550** of independently measuring at least one characteristic of each of the RF receivers from the combined output signal using the test instrument.

As described above in the background, in conventional testing approaches for multi-channel RF communication devices, one must either connect multiple test instruments, or a multi-channel test instrument, to multiple channels in order to measure the multiple channels quickly but expensively, or one can switch a single test instrument from channel to channel in order to measure multiple channels slowly but inexpensively. In contrast, with embodiments of test systems described herein a single test instrument may be employed, which is comparatively inexpensive, but it still allows the channel selection to be done electronically, bringing nearly the same speed as if multiple test instruments were employed but at a much lower cost.

While example embodiments are disclosed herein, one of ordinary skill in the art appreciates that many variations that are in accordance with the present teachings are possible and remain within the scope of the appended claims. The invention therefore is not to be restricted except within the scope of the appended claims.

The invention claimed is:

1. A test system, comprising:

a test signal generator, comprising:

a single channel signal source configured to output a single channel signal, and

a phase shift network configured to receive the single channel signal and in response thereto to output a plurality of RF test signals in parallel with each other, wherein the phase shift network is further configured to shift a phase of one or more of the RF test signals so as to make at least a selected one of the RF test signals orthogonal to the other RF test signals;

a combiner network having a plurality of inputs each configured to receive one of a plurality of receive signals, each receive signal being produced from a corresponding one of a plurality of RF receivers of a device under test (DUT) in response to the RF test signals, wherein the combiner network is configured to combine the plurality of receive signals and to output a combined output signal; and

a single channel measurement instrument configured to receive the combined output signal and to measure therefrom at least one characteristic of each of the RF receivers.

2. The test system of claim **1**, further comprising an optical-to-electrical converter connected between outputs of each of the plurality of RF receivers of the DUT and the inputs of the combiner network.

3. The test system of claim **1**, wherein the phase shift network is an active phase shift network.

4. The test system of claim **3**, wherein the single channel signal source and the phase shift network are configured to output the plurality of RF test signals in parallel with each other.

5. The test system of claim **4**, at least one of the RF test signals is orthogonal to the other RF test signals at a given time.

6. The test system of claim **3**, wherein the active phase shift network comprises an active device adapted to shift the phase for all the RF test signals independently to create at least some orthogonality among RF test signals.

7. The test system of claim **1**, wherein the single channel signal is an RF signal which carries baseband data.

8. The test system of claim **7**, wherein characteristics of the baseband data match those required for reception by the plurality of RF receivers.

9. The test system of claim **1**, wherein the phase shift network is further configured to shift the phase of one or more of the RF test signals to make all of the RF test signals orthogonal to each other.

10. A test system, comprising:

a test signal generator, comprising: a single channel signal source, comprising a processor and a memory, which stores instructions, which when executed by the processor cause the processor to:

generate a plurality of radio frequency (RF) test signals in parallel with each other, wherein at least one of the RF test signals is orthogonal to the other RF test signals at a given time;

apply each of the plurality of RF test signals to a corresponding one of a plurality of RF receivers of a device under test (DUT);

combine a plurality of receive signals each produced from one of the plurality of RF receivers of the DUT in response to the corresponding one of the plurality of RF test signals, to output a combined output signal;

provide the combined output signal to a test instrument; and

employ the test instrument to independently measure at least one characteristic of each of the plurality of RF receivers from the combined output signal.

11. The test system of claim **10**, wherein a transmitter of the DUT generates the plurality of RF test signals in parallel with each other.

12. The test system of claim **11**, wherein the transmitter of the DUT outputs the plurality of RF test signals which are orthogonal to each other.

13. The test system of claim **11**, wherein the instructions, which when executed by the processor to generate the plurality of RF test signals in parallel with each other further, further causes the processor to:

output a single channel signal from a single channel source; and

output from a phase shift network the plurality of RF test signals in parallel with each other in response to the single channel signal.

14. The test system of claim **13**, wherein the instructions, which when executed by the processor, further cause the phase shift network to shift a phase of one or more of the RF test signals so as to make at least one of the RF test signals orthogonal to the other RF test signals.

15. The test system of claim **14**, wherein the instructions, which when executed by the processor, further cause the phase shift network to sequentially shift the phase of each of the RF test signals so as to sequentially make each of the RF test signals orthogonal to the other RF test signals.

16. A tangible, non-transitory computer readable medium that stores instructions, which when executed by a processor, cause the processor to:

generate a plurality of radio frequency (RF) test signals in parallel with each other, wherein at least one of the RF test signals is orthogonal to the other RF test signals at a given time;

apply each of the plurality of RF test signals to a corresponding one of a plurality of RF receivers of a device under test (DUT);

combine a plurality of receive signals each produced from one of the plurality of RF receivers of the DUT in response to the corresponding one of the plurality of RF test signals, to output a combined output signal; and

provide the combined output signal to a test instrument.

17. The tangible non-transitory computer readable medium of claim **16**, wherein a transmitter of the DUT generates the plurality of RF test signals in parallel with each other.

18. The tangible non-transitory computer readable medium of claim **17**, wherein the transmitter of the DUT outputs the plurality of RF test signals which are orthogonal to each other.

19. The tangible non-transitory computer readable medium of claim **17**, wherein the instructions that cause the processor to generate the plurality of RF test signals in parallel with each further cause the processor to:

output a single channel signal from a single channel signal source; and

output the plurality of RF test signals from a phase shift network in parallel with each other in response to the single channel signal, wherein a phase of one or more of the RF test signals is shifted so as to make at least one of the RF test signals orthogonal to the other RF test signals.

20. The tangible non-transitory computer readable medium claim **16**, wherein the instructions further cause the shift in the phase of each of the RF test signals to be sequential so as to sequentially make each of the RF test signals orthogonal to the other RF test signals.

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